High m(T) pion andproton correlations in central Pb Pb collisions at s(NN)**(1/2) = 17-GeV

Bearden, I.G.; Lörstad, Bengt

Published in:
nucl-ex/0305014

2003

High m_T pion and proton correlations in central PbPb collisions at $\sqrt{s_{NN}} = 17$GeV

I.G. Bearden,[1] H. Bøggild,[1] J. Boissevain,[2] P.H.L. Christiansen,[1] L. Conin,[3] J. Dodd,[4] B. Erazmus,[3] S. Esumi,[5] C.W. Fabjan,[6] D. Ferenc,[7] A. Franz,[6] J.J. Gaardhøje,[1] A.G. Hansen,[1] O. Hansen,[1] D. Hardtke,[8] H. van Hecke,[2] E.B. Holzer,[6] T.J. Humanic,[8] P. Hummel,[6] B.V. Jacak,[9] K. Kaimi,[5,*] M. Kaneta,[5] T. Kohama,[5] M. Kopytine,[9] M. Leltchouk,[4] A. Ljubičić Jr.,[7] B. Lörstad,[10] N. Maeda,[5] L. Martin,[3] A. Medvedev,[4] M. Murray,[11] H. Ohnishi,[5] G. Paić,[6] S.U. Pandey,[8] F. Piuz,[6] J. Pluta,[3] V. Polychronakos,[12] M. Potekhin,[4] G. Poulard,[6] D. Reichhold,[8] A. Sakaguchi,[5] J. Schmidt-Sørensen,[10] J. Simon-Gillo,[2] W. Sondheim,[2] T. Sugitate,[5] J.P. Sullivan,[2] Y. Sumi,[5] W.J. Willis,[4] K. Wolf,[11,*] N. Xu,[2] and D.S. Zachary[8]

(The NA44 Collaboration, December 28, 2007)

[1]*Niels Bohr Institute, University of Copenhagen, Denmark*
[2]*Los Alamos National Laboratory, Los Alamos, NM 87545*
[3]*Nuclear Physics Laboratory of Nantes, 44072 Nantes, France*
[4]*Department of Physics, Columbia University, New York, NY 10027*
[5]*Hiroshima University, Higashi-Hiroshima 739-8526, Japan*
[6]*CERN, CH-1211 Geneva 23, Switzerland*
[7]*Rudjer Bošković Institute, Zagreb, Croatia*
[8]*Department of Physics, The Ohio State University, Columbus, OH 43210*
[9]*State University of New York, Stony Brook, NY 11794*
[10]*Department of Physics, University of Lund, S-22362 Lund, Sweden*
[11]*Texas A&M University, College Station, Texas 77843-3366*
[12]*Brookhaven National Laboratory, Upton, New York 11973*

For central PbPb collisions at $\sqrt{S_{nn}} = 17.3$ GeV we have made the first two-dimensional measurement of the pp correlation function. These data extend the range of previous studies of HBT radii by a factor of two in m_T. They are consistent with a hydrodynamic interpretation and microscopic models that include hadronic rescattering and transverse expansion. We also report new data on pion correlations. The two particle correlations of negative pions at $m_T = 0.92$ GeV imply source radii that are smaller than typical hydrodynamic fits and transport model simulations. It is possible that these fast pions may have left the source before the build up of hydrodynamic flow.

PACS numbers: 25.75.Gz, 25.75.Ld

Experimental studies of high-energy nuclear collisions at the AGS, SPS and RHIC accelerators (with $\sqrt{S_{nn}} = 2 \rightarrow 200$ GeV) have revealed many interesting features of hot and dense nuclear matter, and some characteristic signatures of a quark-gluon-plasma phase have been reported [1]. If such a high density state were formed in the initial stages of the reaction the high initial presure would result in a significant transverse flow of the hadrons that originate from the participant zone. Depending on the time scale and the amount of rescattering the system might be expected to be in local thermodynamical equilibrium. This conjecture is supported by the linear increase of the single particle inverse slopes with mass [2, 3].

The Hanbury-Brown Twiss, (HBT), technique uses the interference of particle wavefunctions to infer the angular size of stars or the length scales of nuclear systems from the two particle correlation function [4]. The "radii" measured by HBT can be thought of as "lengths of homogeneity" of the source which depend upon velocity and/or temperature gradients [5, 6, 7]. Heavy Ion HBT measurements over a wide range of energies [8, 9, 10, 11, 12, 13, 14, 15, 16] show a drop of radii with $m_T \equiv \sqrt{p_T^2 + m^2}$ consistent with a hydrodynamical interpretation [17, 18, 19, 20].

Faster particles are more likely to come from initial collisions of the incoming baryons, so at some momentum we might expect the hydrodynamic approach to break down. This may have already been seen at RHIC ($\sqrt{s_{NN}} = 200$GeV) where the strength of elliptic flow falls below the hydrodynamic prediction for $p_T > 2\text{GeV}/c$ [21]. One might expect this to occur at lower p_T at $\sqrt{s_{NN}} = 17$GeV since the multiplicity is lower.

NA44 is a focusing spectrometer [13]. The dipole and quadrupole magnets produce a magnified image of the target in the tracking detectors. This has the advantage that particles that are close in momentum are not necessarily close in position. Since all tracking is done after the magnets we only have to reconstruct straight lines. A high resolution pad chamber sits in the focal plane and gives the magnitude of the momentum. Downstream of the focus the direction of tracks is measured by strip chambers and scintillating hodoscopes. The momentum resolution, including effects of multiple scattering in the target, is $\approx 11\text{MeV}/c$ for p_x, p_y, and p_z.

A beam counter selected events for which single lead ions hit the 3.8mm lead target. Behind the target, two scintillator bars were used to trigger on high multiplicity events. An annular silicon detector with 512 pads which was not part of the trigger measured $dN^{\pm}/d\eta$ ($\eta = \ln\tan\theta/2$) in the pseudorapidity range $1.5 \leq \eta \leq 3.3$. We used events in the top 18% of the multiplicity distribution as we did for our earlier $PbPb$ results [13, 14]. For all data sets except the lower m_T protons the spectrometer was set to accept particles of momentum 6-9 GeV/c and was positioned at 131 mrad with respect to the beam axis. The setting gave a p_T window of 0.7–1.4 GeV/c. For the lower m_T proton sample the momentum window was 5.2–8.0GeV/c and the spectrometer angle was 44 mrad. The resulting p_T range was 0.18–0.50GeV/c. The rapidity range of the data was 2.4–2.9 and the system is symmetric about y=2.9 the center of mass rapidity. The p_T and y acceptance can be found in [22].

Particles were identified by combining time of flight measurements from the hodoscopes with velocity information from three threshold-type gas Cherenkov counters (C1, C2, TIC). C2 was set to fire only on pions. For the higher momentum proton data C1 was used to reject kaons. For the lower m_T proton data kaons were rejected exclusively by their flight time. For the π^- sample the TIC was used to confirm that each track was a pion [23]. Contamination of the samples by other particles was less than 2%. However there is significant feed-down of hyperons into the proton sample, ranging from 28% for the lower m_T sample to 13% for $\langle m_T \rangle = 1.45$ GeV [22]. This tends to smear the correlation function and was accounted for by including a fraction of "fake" protons in the Monte Carlo [24]. The spectrum of hyperons was taken from RQMD with the yield scaled to match NA49 and WA97 results [25, 26].

The two-particle correlation function is defined by

$$C_2(\vec{p}_1, \vec{p}_2) = \frac{P_2(\vec{p}_1, \vec{p}_2)}{P_1(\vec{p}_1)P_1(\vec{p}_2)} \approx \frac{Real(\vec{p}_1, \vec{p}_2)}{Back(\vec{p}_1, \vec{p}_2)}, \quad (1)$$

where the numerator is the joint probability of detecting two particles with momenta $\vec{p}_1$ and $\vec{p}_2$, while the denominator is the product of the probabilities of detecting the single particles. The denominator was obtained by mixing tracks from two randomly selected different events. For protons, the attractive effect of the strong interaction competes with the negative correlation due to Fermi-Dirac statistics and Coulomb repulsion. This results in characteristic "dip-peak" structure in the two-proton correlation function. The height of the correlation peak decreases as the source size increases [27, 28, 29, 30].

The true correlation function is distorted by the momentum resolution, Coulomb repulsion and by residual two particle correlations in the background. The magnitude of these effects depends on the size of the source. For the pions we we evaluated them using an iterative Monte Carlo (MC) simulation. A trial correlation function was used to generate events that we tracked through the spectrometer and analyzed in exactly the same way as the data. The Coulomb wave method was employed to simulate Coulomb effects [31]. This method was used to derive correction factors to the correlation function and the process was repeated until the changes in the corrections from step to step were insignificant [10, 32]. The theoretical correlation function for the pp data was generated by selecting proton pairs from a given source model, calculating the weight due to quantum statistics and final state interactions (strong and Coulomb) and propagating the particles through the Monte Caro. We searched for a source distribution that produced the minimum χ^2 with the data after it was fed through the Monte Carlo [24].

$C_2(\vec{p}_1, \vec{p}_2)$ is a function of 6 variables; 3 for the total momentum $\vec{P} = \vec{p}_1 + \vec{p}_2$, and 3 for the momentum difference $\vec{Q} = \vec{p}_1 - \vec{p}_2$. We decompose $\vec{Q}$ into Q_L, the projection of the momentum difference onto the beam axis, Q_{out} which is parallel to $\vec{P}$ and Q_{side} which is perpendicular to Q_{out} and Q_L. The data are analysed in the Longitudinal Co-Moving System in which $p_{z1} = -p_{z2}$.

To measure correlation functions efficiently we trigger on events with pairs of particles that have a small momentum difference in one direction while allowing large momentum differences in the other two dimensions. In our "vertical setting" the quadrupoles produce a small momentum acceptance in the horizontal space p_x, and a wide acceptance in the vertical direction p_y. Since the spectrometer lies in the horizontal plane this setting allows only a small range in Q_{side} but a large range in Q_{out}. In the "horizontal setting" we have a wide momentum acceptance in p_x and a small acceptance in p_y. This setting allows only a small range in Q_{side} but a large range in Q_{out}. Both settings have a large acceptance in Q_{Long}. The lower m_T proton data were taken in the vertical setting while all other data were taken in the horizontal setting.

For pions we used the maximum likelihood method to fit C2 with

$$C_2(Q_T, Q_L) = D(1 + \lambda e^{-Q_T^2 R_T^2 - Q_L^2 R_L^2}), \quad (2)$$

where R_T and R_L parametrize the size of the source in the transverse and beam directions and D is a free parameter used for normalization. The λ factor is a measure of the chaoticity of quantum states of the source; the fraction of pions from resonances and experimental factors that decrease the correlation function. For these data $Q_T \approx Q_{out}$. Figure 1 shows projections of the correlation function and the fit onto the Q_T and Q_L axis. The λ parameter is larger than for our lower p_T pion measurements. This is expected since the effect of resonances, which tend to wash out C_2 and reduce λ, should be less important as p_T increases. The systematic uncertainties in the fit parameters reflect the effect of (i) cut parameters to define a track, (ii) cut parameters to select pairs, (iii) momentum resolution, (iv) two-track resolution, (v) momentum distribution of particle production in MC, and (vi) fitting to finite bins.

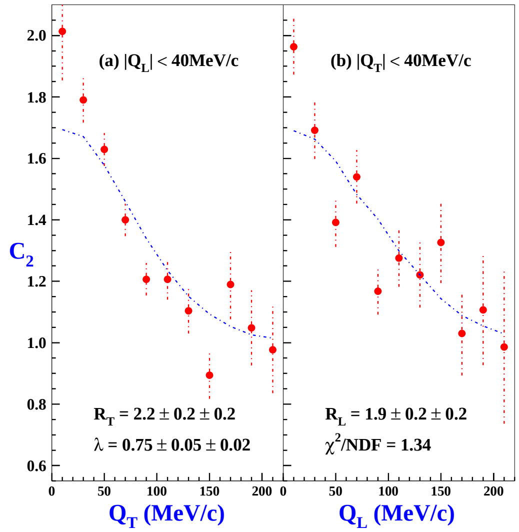

FIG. 1: The π^- correlation function for $\langle m_T \rangle = 0.92GeV$ projected onto the (a) Q_T and (b) the $Q_L$axies. Only statistical errors are shown. The lines are projections of the fit.

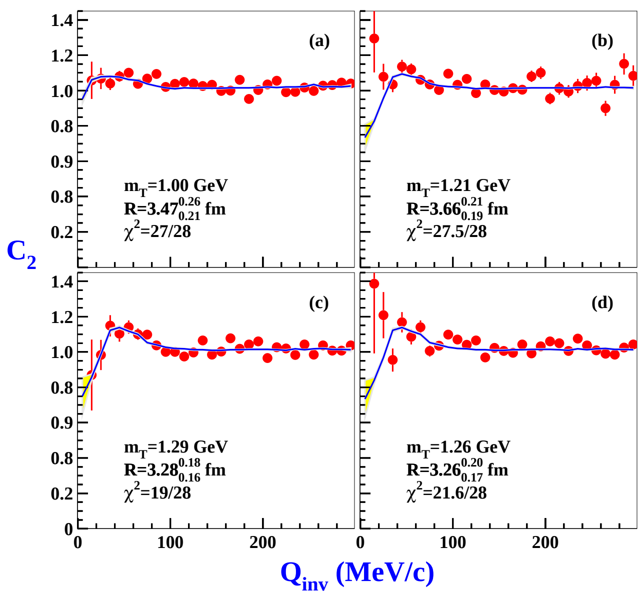

FIG. 2: Projections of the pp correlation function onto the Q_{inv} axis for samples with different $\langle m_T \rangle$. Only statistical errors are shown. The lines show the projections of the fit.

Figure 2 shows the pp correlation function as a function of $Q_{inv} \equiv \sqrt{Q^2 - \Delta E^2}$ for four bins in $\langle m_T \rangle$. At $\langle m_T \rangle =$ 1 GeV our result is consistent with NA49 [33]. R_{inv} increases from pPb to SPb and finally to $PbPb$, [24]. We have also analysed the pp correlation in two dimensions to extract R_T and R_L. Table I summarizes our data and compares them to two models.

RQMD 2.04 is a string model which includes reinteractions between produced hadrons [34]. It gives a good description of the proton data, as it does for our low m_T

TABLE I: PbPb source radii versus m_T from data and models.

	m_T (GeV)	R_T (fm) Data	Rqmd	Nexus	R_L (fm) Data	Rqmd	Nexus
p	1.00	$3.6^{+0.7}_{-0.6}$	3.7	3.1	$3.5^{+1.2}_{-0.9}$	4.6	1.7
	1.21	$4.0^{+0.4}_{-0.3}$	3.6	3.2	$3.5^{+0.6}_{-0.5}$	3.8	1.9
	1.29	$3.2^{+0.2}_{-0.2}$	3.5	3.2	$3.3^{+0.6}_{-0.4}$	3.5	2.0
	1.43	$3.4^{+0.3}_{-0.2}$	3.4	2.8	$2.9^{+0.4}_{-0.3}$	3.1	2.0
π^-	0.92	2.2 ± 0.3	3.9	4.5	1.9 ± 0.3	3.1	2.0

pion results [13, 35]. The decrease of the radii with m_T has already been noticed in the model for pions and results from correlations between position and momentum caused by flow [36]. This decrease is more rapid for R_L than for R_T since the longitudinal flow is stronger. Nexus 2.00 uses pertubative QCD to treat hard nucleon-nucleon interactions and pomeron exchange for soft interactions [37]. It produces proton radii that are too small. Turning on hadronic reinteractions and resonance production results in larger radii closer to the data. RQMD fails to reproduce both pion radii at $m_T = 0.92$GeV. Nexus reproduces R_L but overestimates R_T by a factor of two.

Under certain conditions [17] one can derive analytic expressions for the radii:

$$\frac{1}{R_T^2} \approx \frac{1}{R^2}\left(1 + \eta_f^2 \frac{m_T}{T}\right); \quad (3)$$

$$\frac{1}{R_L^2} \approx \frac{1}{\tau_0^2 \Delta\eta^2}\left(1 + \Delta\eta^2 \frac{m_T}{T}\right); \quad (4)$$

where R is the geometrical size of the source, τ_0 and T_0 are the time and temperature of freeze-out, $\delta\eta$ represents the width in rapidity and η_f is the transverse rapidity. The radii also depend on the particle's mass but this effect is very small for reasonable values of η_f. Since $\eta_f < \Delta\eta$, R_L should drop more rapidly with m_T than R_T because the longitudinal flow is stronger than the transverse flow.

Figure 3 shows the m_T dependence of R_T and R_L for all NA44 correlation and coalescence measurements [13, 14, 38]. The proton coalescence analysis gives only one radius which is mainly sensitive to the transverse size, (see Eqn. 6.3 of [39]). These radii are in good agrement with the pp correlation data. R_L decreases faster with m_T than does R_T as expected from RQMD simulations and Eqns 3 and 4. The lines in Fig. 3 are the result of fitting our systematics to the form $1/R^2 = p0 + p1 \cdot M_T$. The bands show the errors on the fits. The χ^2/ndf is poor because the π^- radii at $\langle m_T \rangle \approx 0.92$ GeV are smaller than the trend expected from our other data. Removing the high m_T π^- radii from the fit gives $\chi^2/\text{ndf} \approx 1$ but has a negligible effect on the fit parameters.

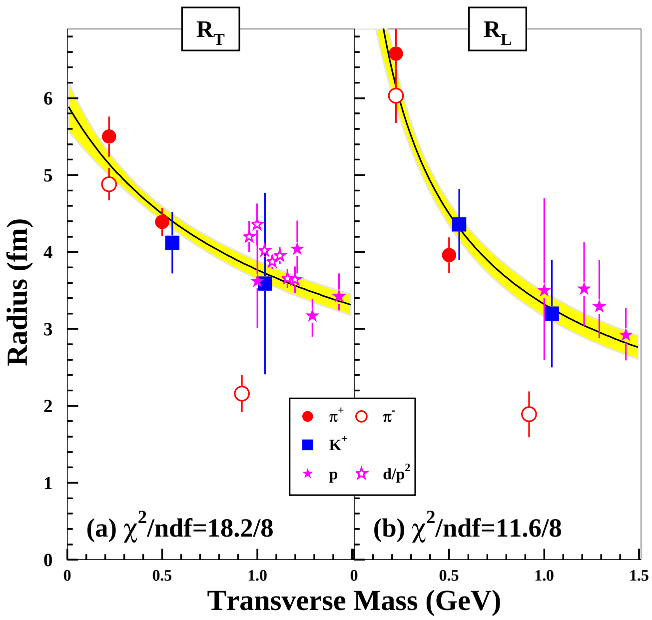

FIG. 3: NA44 pion, kaon and proton source sizes versus m_T [13, 14, 38]. Both radii are fit to the form $1/R^2 = p0+p1 \cdot M_T$. The lines and bands show the results and errors of the fits.

At $m_T = 0.22$GeV the negative pions have source radii that are 9-11% smaller than for the positive pions. However the π^- and π^+ correlation functions themselves are consistent and non Gaussian in shape [13]. RQMD simulations suggest that this is due to resonance decays, particularly of the ω. Resonances tend to reduce the λ parameter when fitting C_2 to Eqn. 2. This effect decreases rapidly with p_T [36]. It is possible that interaction with the residual nuclear charge could reduce the π^- radius as compared to the π^+ radius. Again this effect should be stronger at low p_T.

In summary, we have made the first two-dimensional measurement of the pp correlation function in relativistic nucleus-nucleus collisions. NA44 has measured HBT radii over a significantly larger m_T range than any other experiment. The pp data, and all our previous HBT results, are consistent with a hydrodynamical interpretation and microscopic models that include hadronic rescattering and transverse expansion. R_L drops more rapidly with m_T than R_T because the longitudinal flow is stronger than the transverse flow. At $m_T = 0.92$GeV we find that the π^- radii are somewhat smaller than expected from the trend of our other data and are not easily explained by either hydrodynamic fits or the RQMD model. It may be that these fast pions left the source before the buildup of flow and so offer a glimpse of the hadronic system at an early point in its expansion.

We thank the staff of the CERN accelerators for their excellent work. We are grateful for financial support from the Danish Natural Science Research Council; the Japanese Society for the Promotion of Science and the Ministry of Education, Science and Culture; the Swedish Science Research Council; the Austrian Fond für Förderung der Wissenschaftlichen Forschung; the US National Science Foundation and the Department of Energy.

---

* Deceased

[1] *Proceedings of Quark Matter 2001*, T.J. Hallman, D.E. Kharzeev, J.T. Mitchell and T. Ullrich , [Nucl. Phys. **A698**, 1c-676c (2002) and Quark Matter 2002 http://alice-france.in2p3.fr/qm2002/ .
[2] I. G. Bearden *et al.*, Phys. Rev. Lett. **78**, 2080 (1997).
[3] I. G. Bearden *et al.*, Eur. Phys. J. C **23**, 237 (2002).
[4] R. Hanbury-Brown, R. Q. Twiss, Nature **178** 1046 (1956) and G. Goldharber, S. Goldharber, W. Lee, A. Pais Phys. Rev. **120** 300 (1960).
[5] Yu. M. Sinyukov, Nucl. Phys. **A566** 589c (1994).
[6] T. Csörgő and B. Lörstad, Phys. Rev. **C 54** 1390 (1996).
[7] U. A. Weidemann and U. Heinz, Phys. Rep **319** 145 (1999).
[8] L. Ahle, *et al.*, Phys. Rev. **C66** 054906 (2002).
[9] A. Bamberger *et al.*, Phys. Lett. **B203**, 320 (1988); T. Alber *et al.*, Z. Phys. **C66**, 77 (1995).
[10] H. Bøggild *et al.*, Phys. Lett. **B302**, 510 (1993).
[11] H. Appelshäuser *et al.*, Eur. Phys. J. **C2**, 661 (1998).
[12] M. M. Aggarwal *et al.*, Eur. Phys. J. **C16**, 445 (2000).
[13] I. G. Bearden *et al.*, Phys. Rev. **C58**, 1656 (1998).
[14] I. G.!Bearden *et al.*, Phys. Rev. Lett. **87**, 112301 (2001).
[15] C. Adler *et al.*, Phys. Rev. Lett. **87**, 082301 (2001).
[16] K. Adcox *et al.*, Phys. Rev. Lett. **88**, 192302 (2002).
[17] U. W. Heinz and B. V. Jacak, Ann. Rev Nucl. Part. Sci **49** 529 (1999).
[18] S. V. Akkelin and Yu. M. Sinyukov, Phys. Lett. **B356**, 525 (1995).
[19] U. A. Wiedemann, P. Scotto, and U. Heinz, Phys. Rev. **C53**, 918 (1996).
[20] T. Csörgő and B. Lörstad, Phys. Rev. **C54**, 1390 (1996).
[21] C. Adler *et al.*, Phys.Rev.Lett. 90 032301 (2003).
[22] I. G. Bearden *et al.*, Phys. Rev. C 66, 044907 (2002).
[23] A. Braem *et al.*, Nucl. Inst. Meth. A **409** 426 (1998).
[24] H. Bøggild *et al.*, Phys. Lett. **B458** 181 (1999).
[25] S. V. Afanasiev *et al.* J. Phys. G **28**, 1761 (2002)
[26] F. Antinori *et al.*, Eur. Phys. J. **C14** 633 (2000).
[27] S. E. Koonin, Phys. Lett. **70B** 43 (1977).
[28] R. Lednicky, V.L. Lyuboshitz, Yad. Fiz. **35** 1316 (1982) (Sov. J. Nucl. Phys. **35** 770(1982)).
[29] S. Pratt, M.B. Tsang, Phys. Rev. **C36** 2390 (1987).
[30] C. Ghisalberti *et al.*, Nucl. Phys. **A583** 401c (1995).
[31] S. Pratt, Phys. Rev. **D33**, 72 (1986).
[32] W. A. Zajc *et al.*, Phys. Rev. **C29**, 2173 (1984).
[33] H. Appelshauser *et al.* Phys. Lett. B **467**, 21 (1999).
[34] H. Sorge, Phys Rev Cbf 52 3291 (1995).
[35] J. P. Sullivan *et al.*, Nucl. Phys. A **566**, 531C (1994).
[36] D. E. Fields *et al.*, Phys. Rev. C **52**, 986 (1995).
[37] H.J.Drescher, M.Hladik, S.Ostapchenko, T.Pierog and K.Werner, Phys.Rev. C **65** 054902 (2002). Phys. Lett. B **97**, 363 (1980).

[38] M. Murray and B. Holzer, Phys. Rev. **C63** 054901 (2001).
[39] R. Scheibl and U. Heinz, Phys. Rev. C **59**, 1585 (1999).